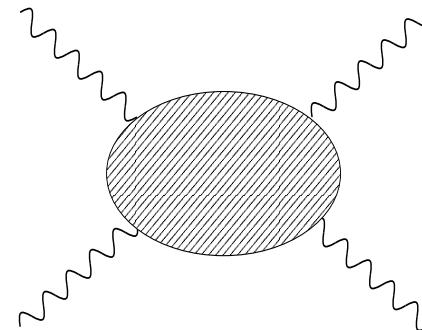

Beyond the Standard Model

Theoretical perspectives

Bogdan Dobrescu (*Fermilab*)

$W_L^+ W_L^-$ scattering:



Perturbatively: $\sigma (W_L^+ W_L^- \rightarrow W_L^+ W_L^-) \approx \frac{G_F^2 s}{16\pi}$

This makes sense only up to $\sqrt{s} \sim 1$ TeV.

(Lee, Quigg, Thacker, 1977)

At higher energy scales:

- ★ A new particle: Higgs boson
 - or
- ★ New strong interaction (perturbative expansion not valid)
 - or
- ★ Quantum field theory description breaks down

Standard Model

Fermion and scalar gauge charges:

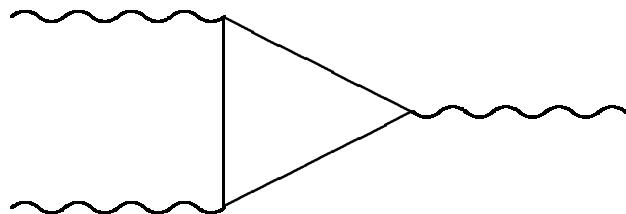
		$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
quark doublet:	$q_L^i = (u_L^i, d_L^i)$	3	2	1/3
right-handed up-type quark:	u_R^i	3	1	4/3
right-handed down-type quark:	d_R^i	3	1	-2/3
lepton doublet:	$l_L^i = (\nu_L^i, e_L^i)$	1	2	-1
right-handed charged lepton:	e_R^i	1	1	-2
Higgs doublet:	H	1	2	+1

$i = 1, 2, 3$ labels the fermion generations.

Anomaly cancellation

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



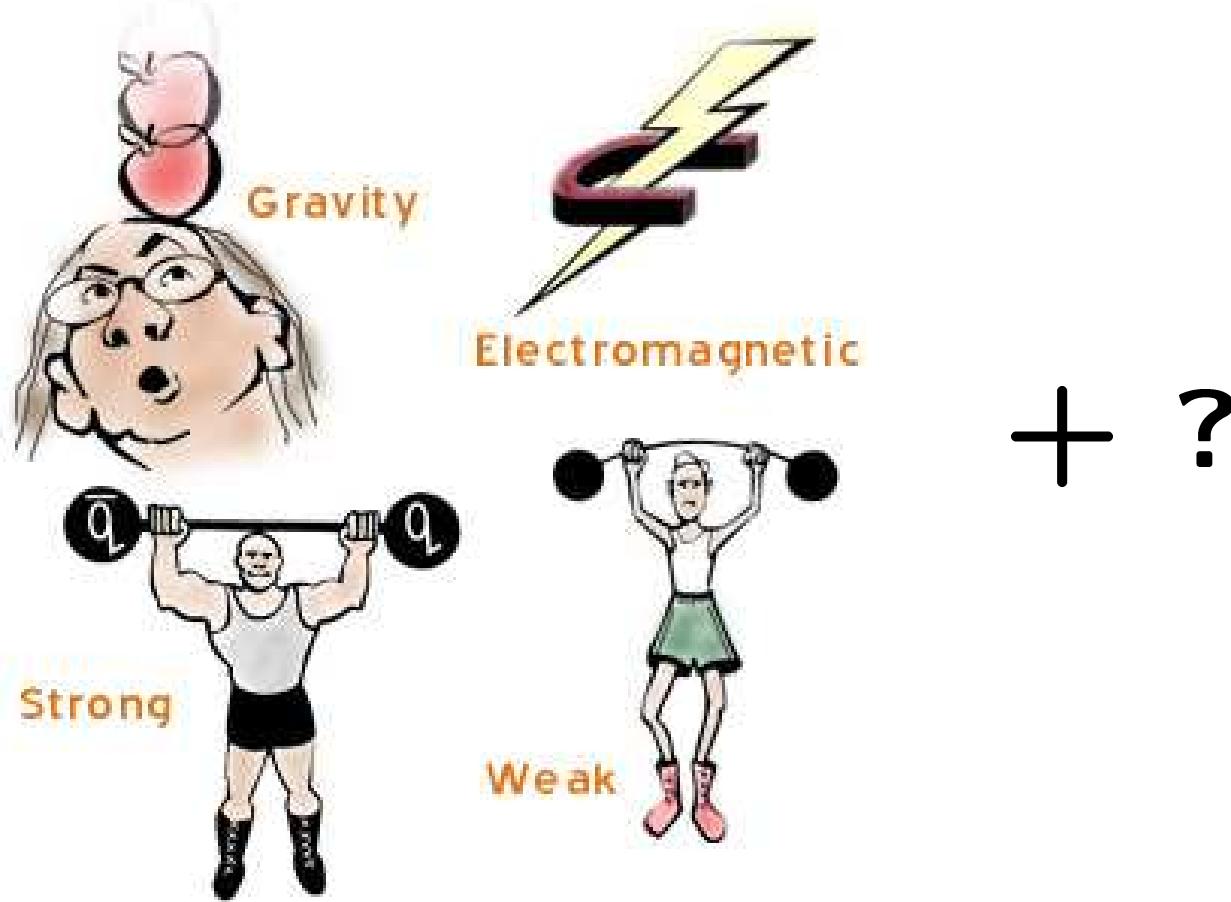
Standard Model: anomalies cancel within each generation

$$[SU(3)]^2 U(1): \quad 2(1/3) + (-4/3) + (2/3) = 0$$

$$[SU(2)]^2 U(1): \quad 3(1/3) + (-1) = 0$$

$$[U(1)]^3: \quad 3[2(1/3)^3 + (-4/3)^3 + (2/3)^3] + 2(-1)^3 + (-2)^3 = 0$$

$$U(1)\text{-gravitational:} \quad 2(1/3) + (-4/3) + (2/3) = 0$$



Could there exist new gauge bosons?

Yes, if they are sufficiently heavy ...

(new gauge symmetry must be spontaneously broken)

Z' gauge boson

Consider an $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_z$ gauge symmetry spontaneously broken down to $SU(3)_C \times U(1)_{\text{em}}$ by the VEVs of a doublet H and an $SU(2)_W$ -singlet scalar, φ .

Three electrically-neutral gauge bosons: γ, Z, Z' .

Z' interactions with fermions in the Lagrangian: $\sum_f (z_f g_z) \bar{f} \gamma^\mu f Z'_\mu$

“Nonexotic” Z' (*Appelquist, Dobrescu, Hopper: hep-ph/0212073*)

Assume:

- generation-independent charges,
- quark and lepton masses as in the standard model,
- no new fermions other than an arbitrary number of ν_R 's

Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_z$
q_L^i	3	2	1/3	z_q
u_R^i	3	1	4/3	z_u
d_R^i	3	1	-2/3	$2z_q - z_u$
l_L^i	1	2	-1	$-3z_q$
e_R^i	1	1	-2	$-2z_q - z_u$
ν_R^k , $k = 1, \dots, n$	1	1	0	z_k
H	1	2	+1	$-z_q + z_u$
φ	1	1	0	1

$[SU(3)_C]^2 U(1)_z$, $[SU(2)_W]^2 U(1)_z$, $U(1)_Y [U(1)_z]^2$ and
 $[U(1)_Y]^2 U(1)_z$ anomalies cancel

Gravitational- $U(1)_z$ and $[U(1)_z]^3$ anomaly cancellation conditions:

$$\frac{1}{3} \sum_{k=1}^n z_k = -4z_q + z_u$$

$$\left(\sum_{k=1}^n z_k \right)^3 = 9 \sum_{k=1}^n z_k^3$$

Nontrivial solutions only if the number of ν_R is $n \geq 3$.

(e.g. $z_1 = z_2 = z_3 = -4z_q + z_u$)

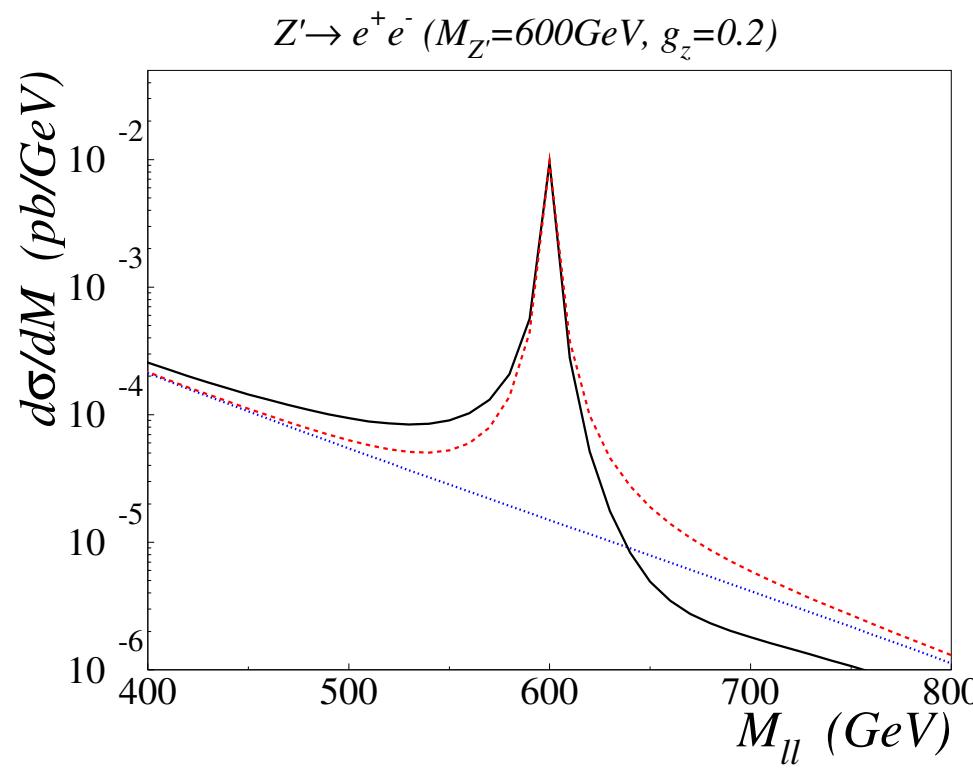
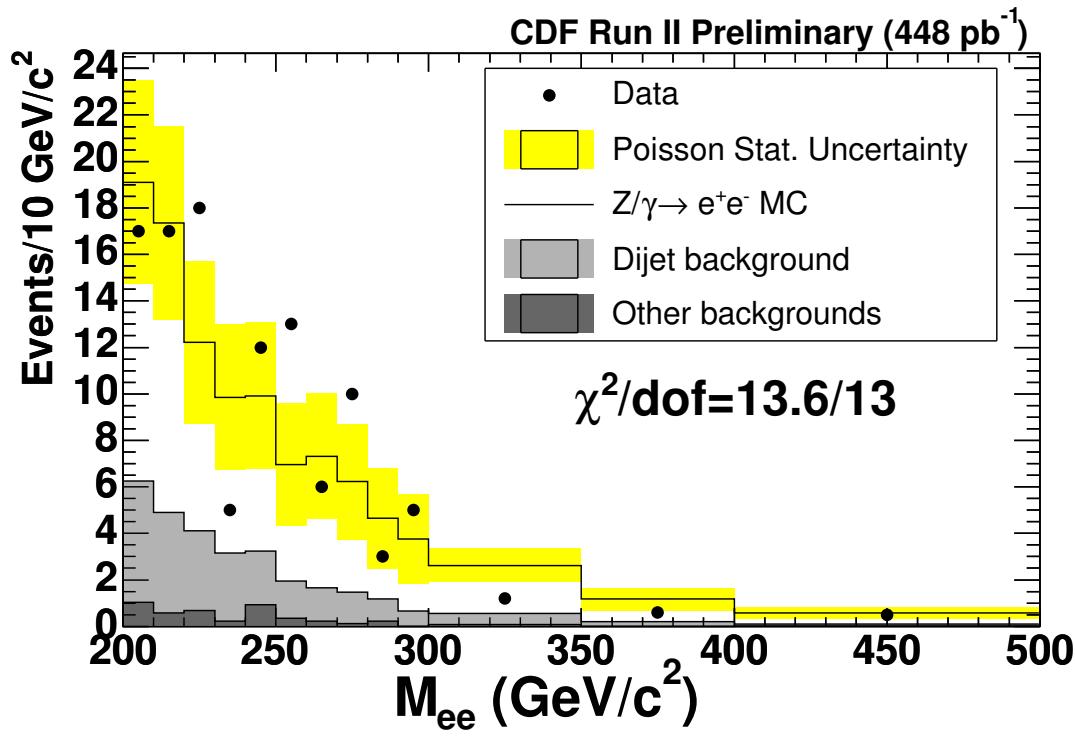
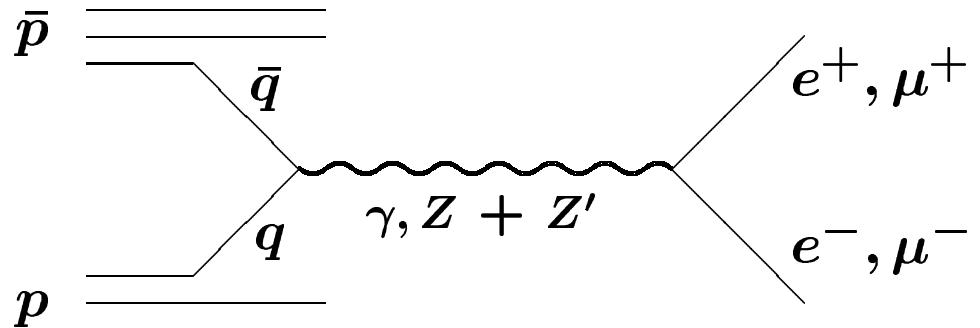
Special case: $SU(3)_C \times SU(2)_W \times U(1)_Y \times \textcolor{red}{U(1)_{B-L}}$

Charges given by the baryon minus lepton number:

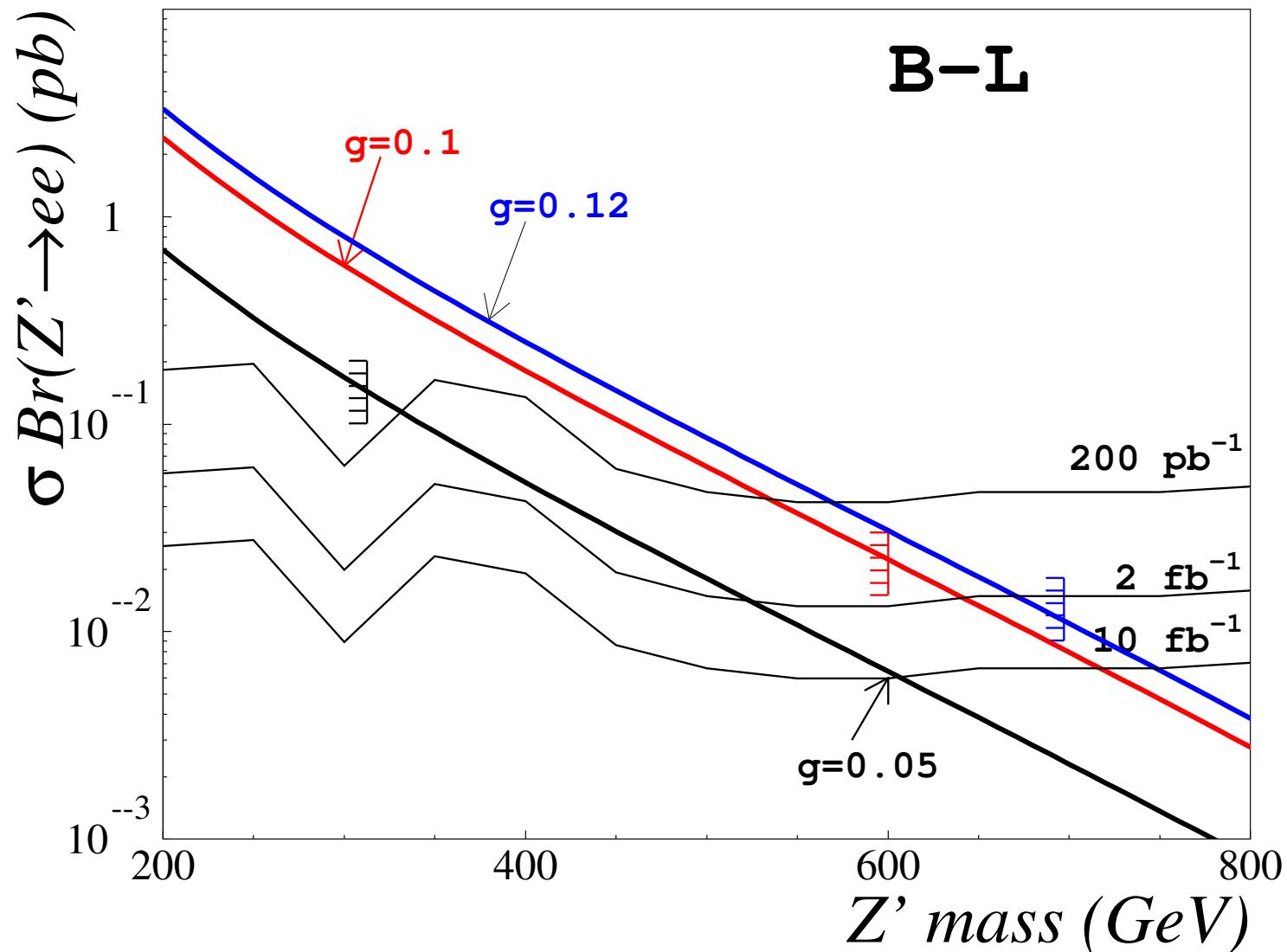
$$z_q = z_u = z_d = -\frac{z_l}{3} = -\frac{z_e}{3} = -\frac{z_\nu}{3} , \quad z_H = 0$$

no Z' - Z mixing at tree level \Rightarrow no strong constraints from electroweak measurements

Z' searches at the Tevatron



Z' searches at the Tevatron:



More general charges are allowed in the presence of new fermions:

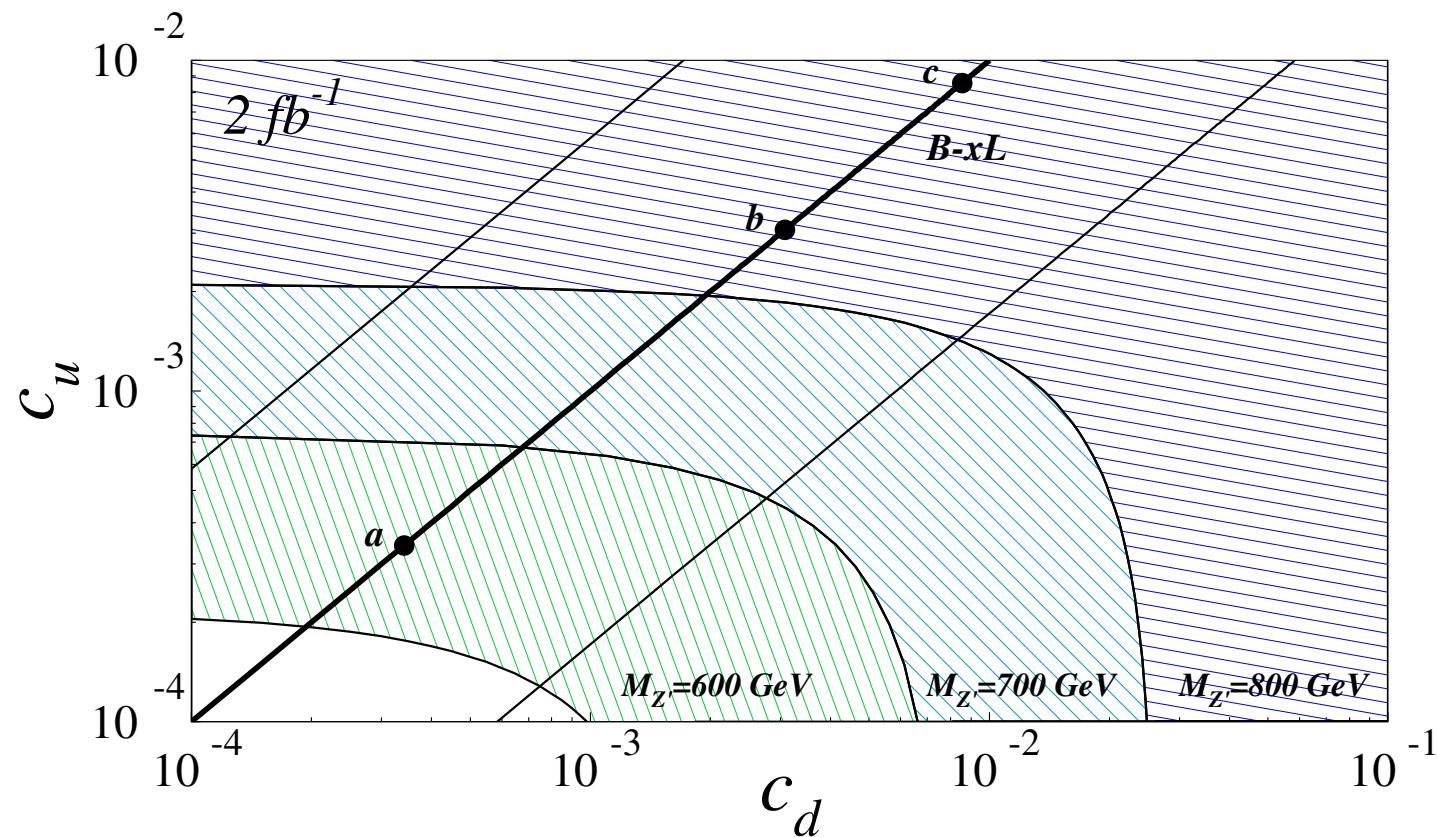
	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
q_L	3	2	1/3	1/3	1/3	1/3	0
u_R	3	1	4/3	1/3	$x/3$	-1/3	$-x/3$
d_R	3	1	-2/3	1/3	$(2-x)/3$	$-x/3$	1/3
l_L	1	2	-1	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	1	1	-2	$-x$	$-(2+x)/3$	-1/3	$x/3$
ν_R	1	1	0	-1	$(-4+x)/3$	$(-2+x)/3$	$-x/3$
ν'_R$	.	.	.	.	.	-1-x/3$	.
ψ_L^l	1	2	-1	-1	.	$-(1+x)/3$	$-2x/5$
ψ_R^l	.	.	.	$-x$	.	2/3	$(-1+x/5)/3$
ψ_L^e	1	1	-2	-1	.	.	.
ψ_R^e	.	.	.	$-x$	.	.	.
ψ_L^d	3	1	-2/3	.	.	-2/3	$(1-4x/5)/3$
ψ_R^d$	.	.	.	.	.	(1+x)/3$	$x/15$

A user-friendly parametrization:

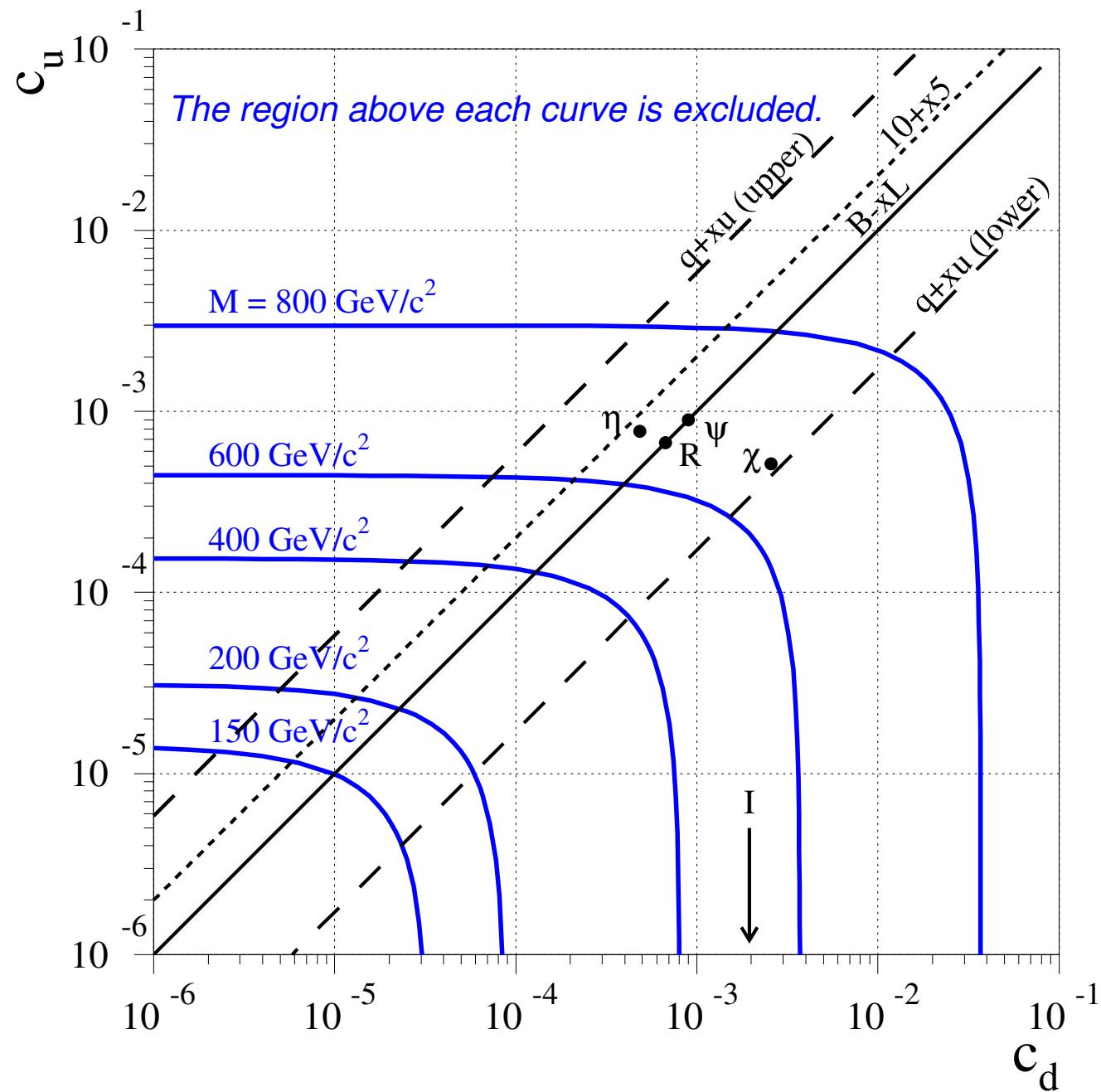
$$\sigma(p\bar{p} \rightarrow Z'X \rightarrow l^+l^-X) = \frac{\pi}{48 s} \left[c_u w_u \left(\frac{M_{Z'}^2}{s}, M_{Z'} \right) + c_d w_d \left(\frac{M_{Z'}^2}{s}, M_{Z'} \right) \right]$$

All the information about charges is contained in:

$$c_{u,d} = g_z^2 (z_q^2 + z_{u,d}^2) \text{Br}(Z' \rightarrow l^+l^-)$$



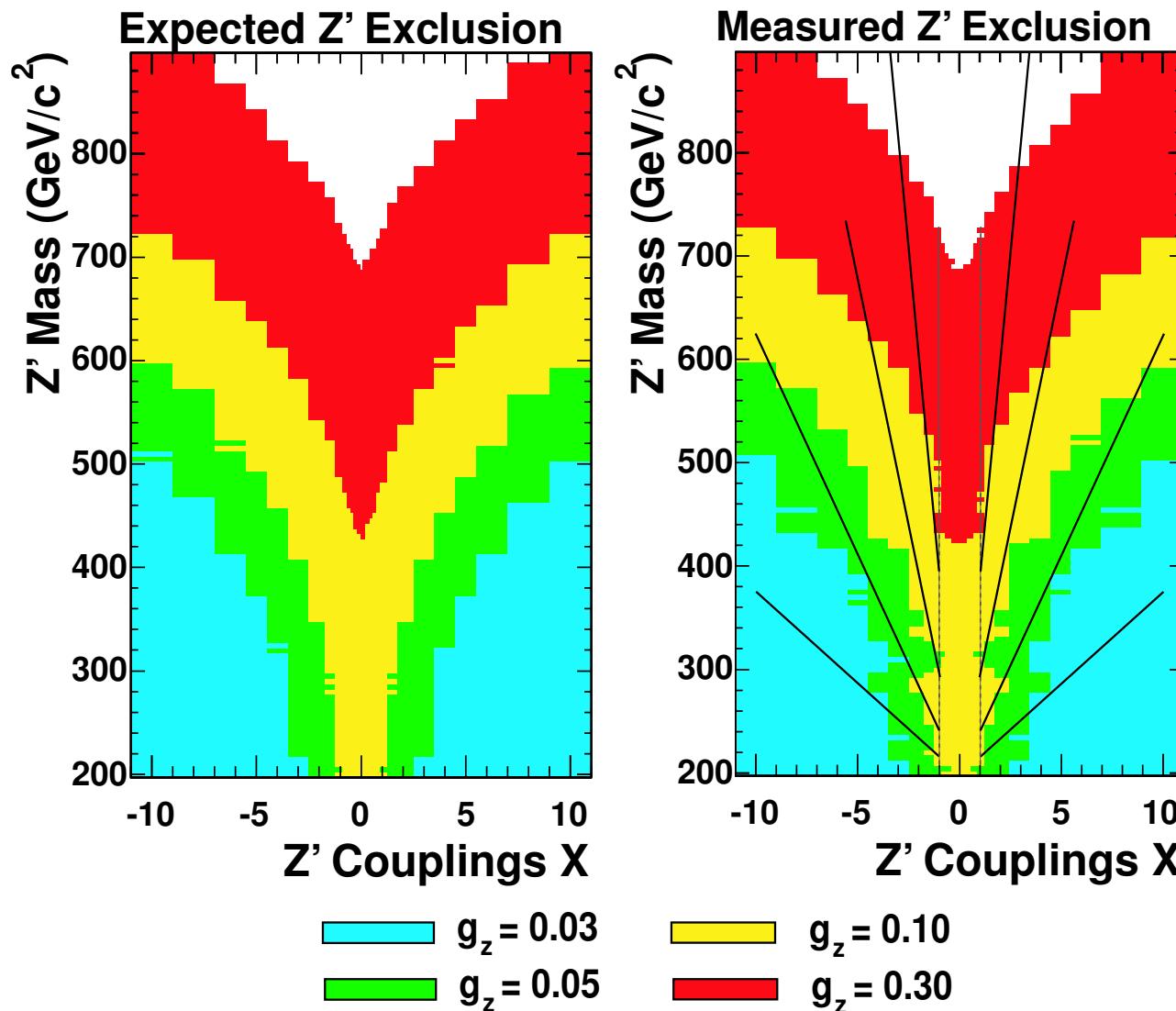
CDF - preliminary (200 pb^{-1}) – see Greg Veramendi's JETP talk on May 13, 2005



see Greg Veramendi's JETP talk on May 13, 2005

10+ $\bar{5}$ models

CDF Run II Preliminary (448 pb $^{-1}$)



LHC:

$$\sigma(pp \rightarrow Z'X \rightarrow l^+l^-X) = \frac{\pi}{48s} \left[c_u w'_u \left(\frac{M_{Z'}^2}{s}, M_{Z'} \right) + c_d w'_d \left(\frac{M_{Z'}^2}{s}, M_{Z'} \right) \right]$$

w'_u and w'_d contain all the information about QCD:

values at the LHC are different than at the Tevatron

⇒ c_u and c_d can be determined independently if a Z' is observed at both the Tevatron and the LHC.

More information about Z' couplings ($U(1)_z$ charges) can be extracted from angular distributions, etc.

Even when $z_q = z_u = z_d = z_l = z_e = 0$
there can still be interactions of the standard model fields with the new massless gauge boson:
higher-dimensional operators!

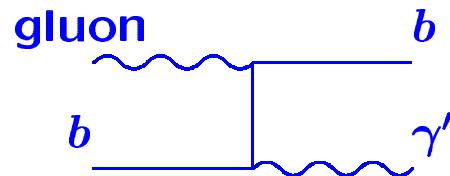
A γ' may couple to quarks and leptons via dimension-6 operators suppressed by a scale $\lesssim 1 \text{ TeV}$!

BD, Phys. Rev. Lett. 94, 151802 (2005)

Tevatron - “factory” of heavy particles, but also:

γ' production at the Tevatron

Example: monojet + missing energy



Tevatron - “factory” of massless particles!

Vector-like quarks

q_L, q_R : same gauge charges

⇒ vector-like quarks have gauge invariant masses

unlike all elementary fermions discovered so far!

Predicted in many models:

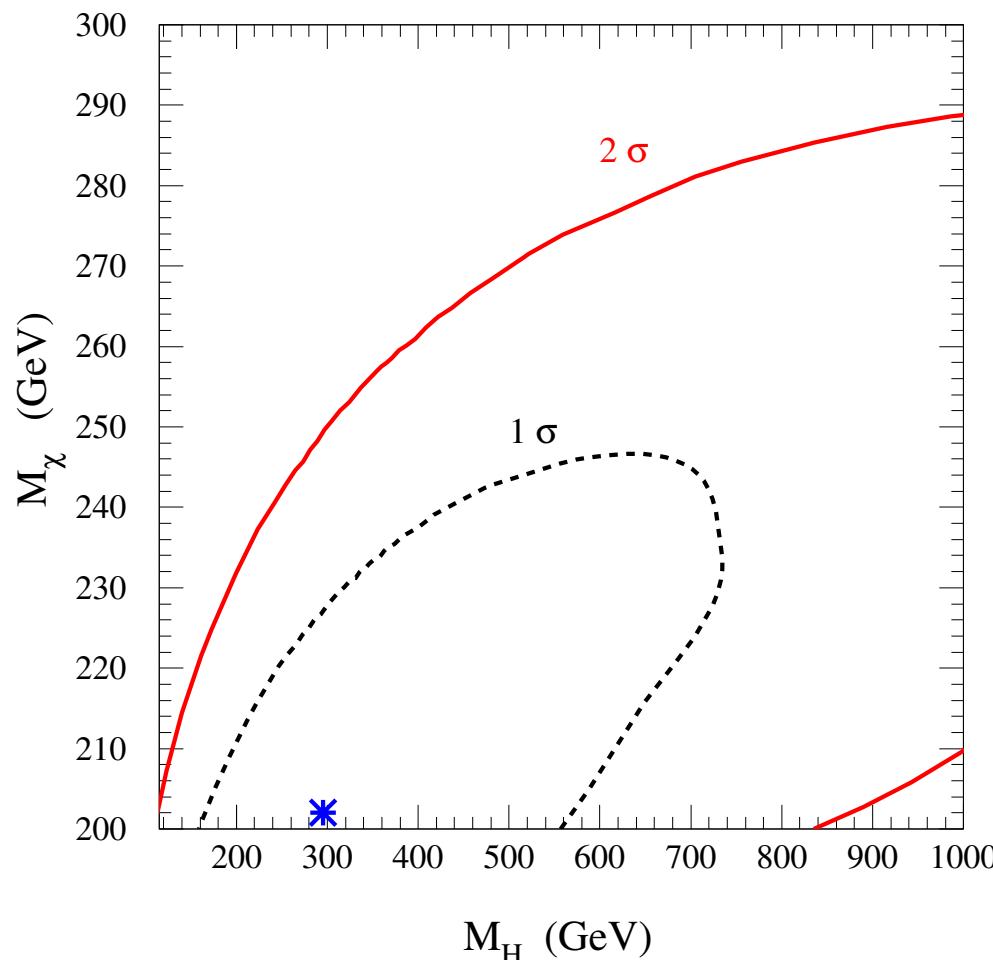
- “Top-quark seesaw” model (*Dobrescu, Hill, 1997*)
→ Higgs doublet is composite
- “Little Higgs” models (*Arkani-Hamed et al, 2002*)
→ no quadratic divergences at 1-loop

- “Beautiful mirrors” (Choudhury, Tait, Wagner, 2001)

→ explains A_{FB}^b ;

→ signal in Run II: $b' \rightarrow bZ$ for $m_{b'} < 300$ GeV

(whole region of parameter space can
be explored with 2 fb^{-1})



Fermions in a compact dimension



Lorentz group in 5D \Rightarrow vector-like fermions: $\chi = \chi_L + \chi_R$

Chiral boundary conditions:

$$\begin{aligned}\chi_L(x^\mu, 0) &= \chi_L(x^\mu, \pi R) = 0 \\ \frac{\partial}{\partial y} \chi_R(x^\mu, 0) &= \frac{\partial}{\partial y} \chi_R(x^\mu, \pi R) = 0\end{aligned}$$

Kaluza-Klein decomposition:

$$\chi = \frac{1}{\sqrt{\pi R}} \left\{ \chi_R^0(x^\mu) + \sqrt{2} \sum_{j \geq 1} \left[\chi_R^j(x^\mu) \cos \left(\frac{\pi j y}{L} \right) + \chi_L^j(x^\mu) \sin \left(\frac{\pi j y}{L} \right) \right] \right\}$$

Kaluza-Klein modes, $\chi^j(x)$: a tower of massive particles

$$m_j^2 = m_0^2 + \frac{j^2}{R^2}$$

Universal Extra Dimensions

T. Appelquist, H.-C. Cheng, B. Dobrescu, Phys.Rev.D64 (2001)

All Standard Model particles propagate in $D \geq 5$ dimensions.

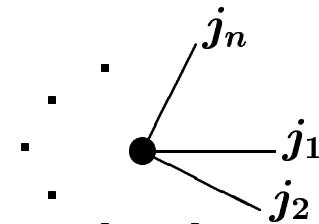
Kaluza-Klein modes are states of definite momentum along the compact dimensions.

Momentum conservation \rightarrow KK-number conservation

$$\mathcal{L}_{4D} = \int dy \mathcal{L}_{5D}$$

At each interaction vertex:

$$j_1 \pm j_2 \pm \dots \pm j_n = 0 \text{ for a certain choice of } \pm$$

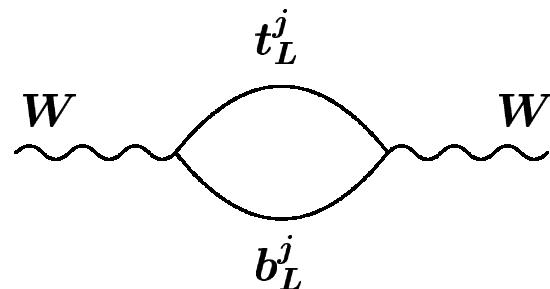


In particular: $0 \pm \dots \pm 0 \neq 1$

\Rightarrow tree-level exchange of KK modes does not contribute to currently measurable quantities

\Rightarrow no single KK 1-mode production at colliders

Bounds from one-loop shifts in W and Z masses, and other observables:



$$\frac{1}{R} \gtrsim 300 \text{ GeV}$$

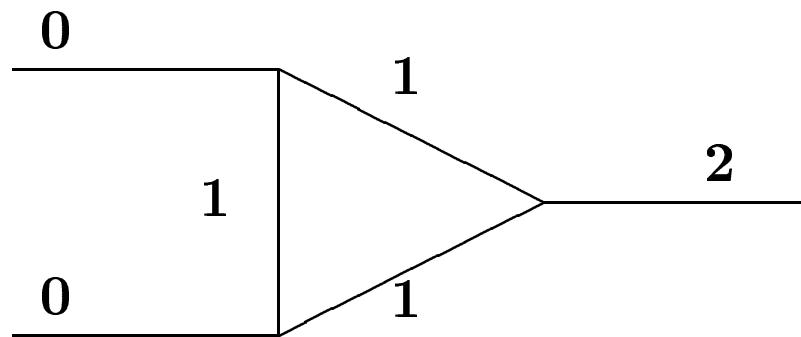
- Pair production of KK 1-modes at colliders: cascade decays to $4l + \cancel{E}_T$ (soft leptons). Could be discovered soon!

(Cheng, Matchev, Schmaltz, hep-ph/0205314)

At one-loop level: $j_1 \pm j_2 \pm \dots \pm j_n = \text{even}$

KK parity is conserved: $(-1)^j$

At colliders: s -channel production of the 2-modes



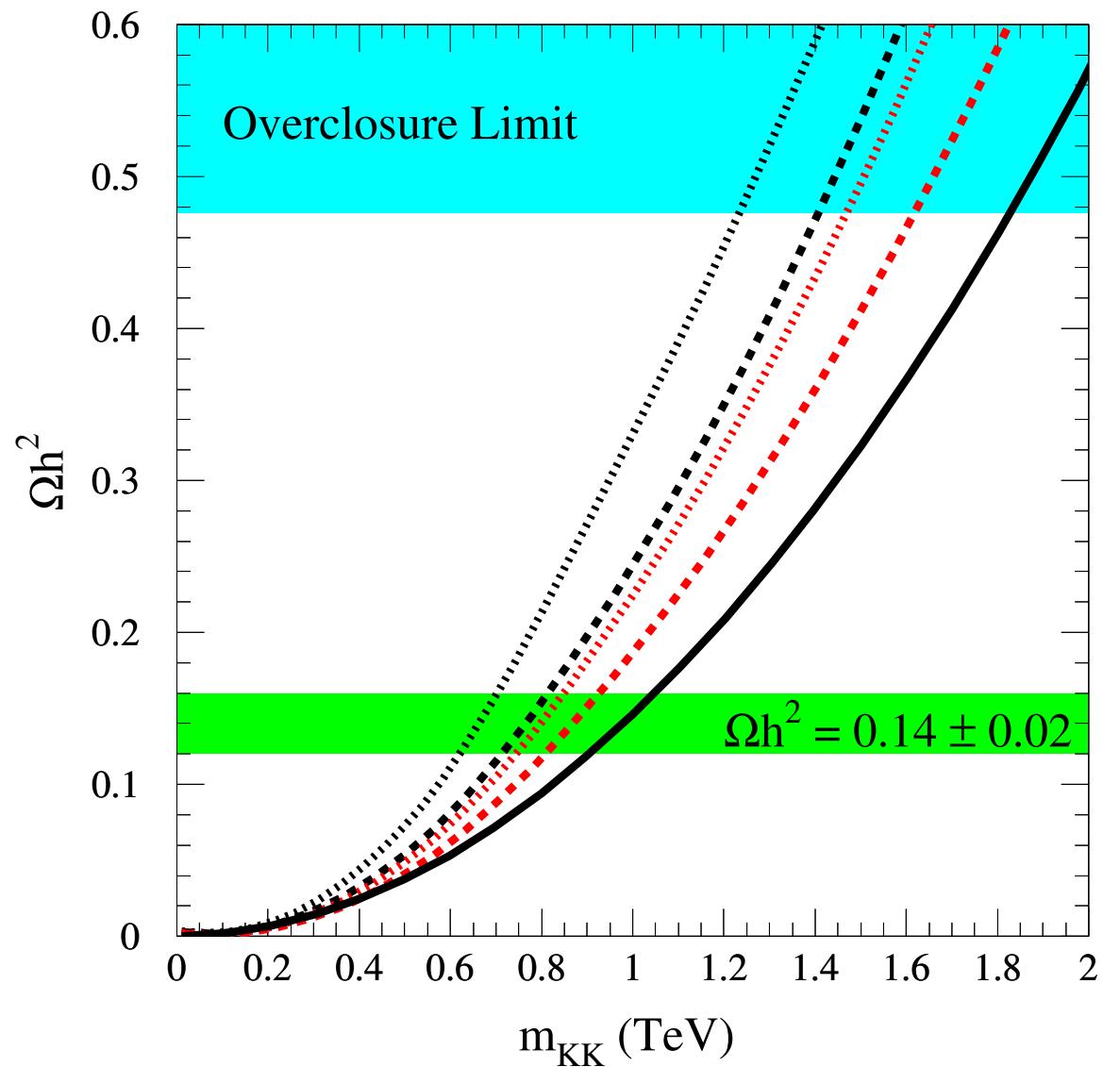
Second-level masses: $\sim 2/R$.

**Decay into two 1-modes followed by cascade decays
(soft leptons, jets and E_T).**

**Lightest KK particle
is stable in UED:**

**$\gamma^{(1)}$ is a viable dark
matter candidate**

(from Servant, Tait,
[hep-ph/0206071](#))



Many other models in extra dimensions:

e.g., “Opaque branes” - localized operators (Carena, Tait, Wagner, et al, 2002)

Six-Dimensional Standard Model

6D is special...

- Global $SU(2)_W$ anomaly cancellation requires 3 mod 3 quark and lepton generations!
- Gravitational anomaly cancellation in 6D requires one right-handed neutrino per generation, and 6D Lorentz symmetry allows ν masses only of the Dirac type.
- Proton lifetime is sufficiently long

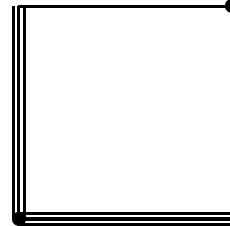
Compactification of two extra dimensions

Chiral boundary conditions on a square

(Dobrescu, Ponton, hep-ph/0401032; work with G. Burdman and E. Ponton)

$$\Phi(y, 0) = e^{i\theta} \Phi(0, y), \dots$$

$$\Rightarrow \theta = n\pi/2$$



Symmetry: $Z_8 \times Z_2^{\text{KK}}$ ⇒ proton stability and dark matter candidate

The (1,1) mode has a mass of $\sqrt{2}/R$, and has KK parity +

Signals at the Tevatron and LHC:

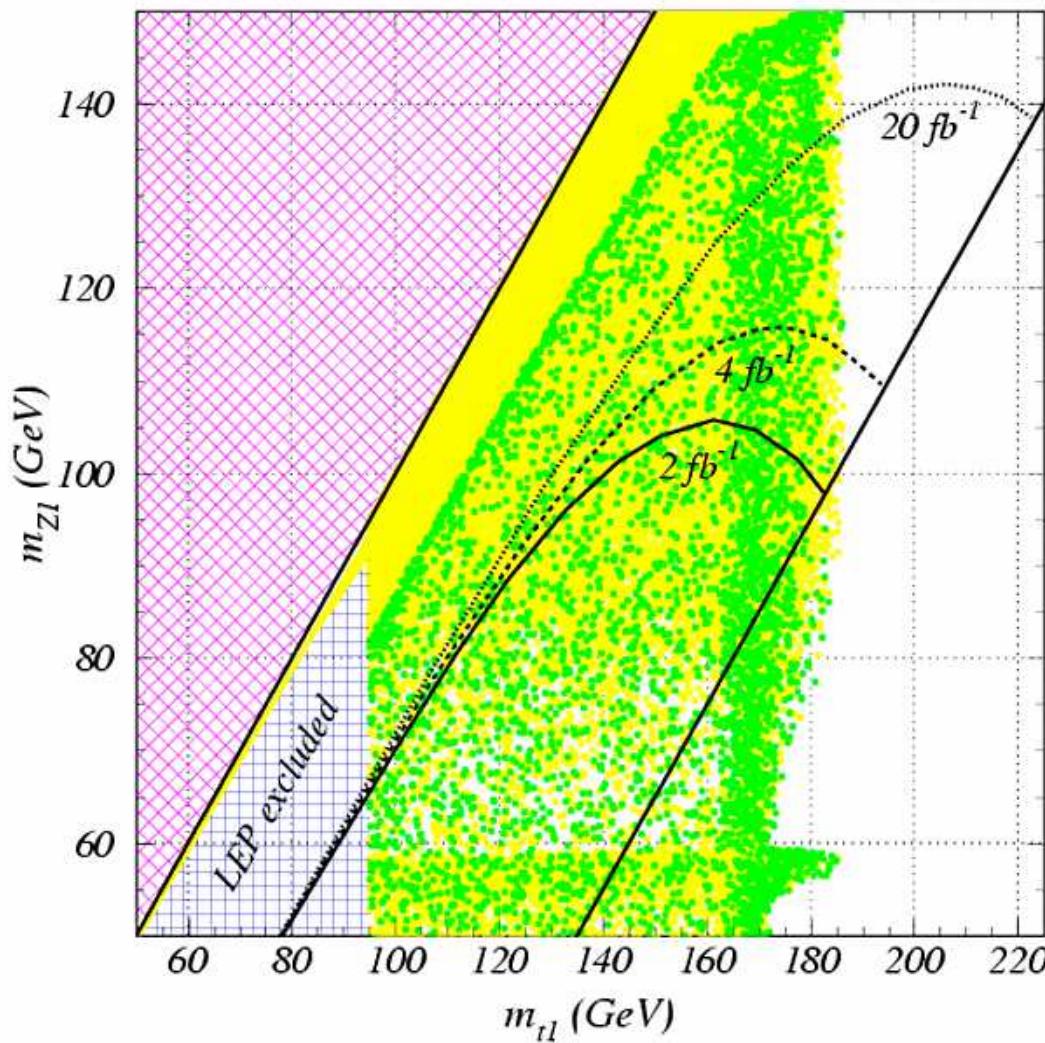
**s -channel production of a (1,1) mode gluon,
followed by a cascade decay to $\gamma^{(1,1)} +$ soft leptons and jets,
and $\gamma^{(1,1)} \rightarrow l^+l^-$ (high p_T leptons).**

Light stop at the Tevatron

Balazs, Carena, Wagner, hep-ph/0403224

$$\tilde{t} \rightarrow c \tilde{\chi}$$

MSSM



Conclusions

New physics searches can be done based on:

- a certain signature (ee , $\gamma\gamma$, ...),
- a certain particle (Z' , a vector-like quark, ...),
- a certain model (MSSM, universal extra dimensions, ...).

In all these categories there are new searches that remain to be done!

This is a great time to analyze the CDF and D0 data; we are all excited awaiting to learn what is in there.